Reducing the Impact Land Use Changes have on Sediment and Phosphorus Loadings to Urban Impoundments – A Case Study

Réduire l'impact des changements d'occupation des sols sur les charges de sédiments et de phosphore à l'aval bassins urbains - Etude de cas

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RÉSUMÉ

L'impact de la perte de sol dû aux processus urbains d'érosion est un problème majeur auquel sont confrontés les décisionnaires, tant à l'échelle nationale que locale. L'objet de cette étude était de quantifier l'impact de l'érosion du sol résultant des changements d'affectation des sols, sur les dépôts urbains. La gestion des charges de sédiments combinée avec la réduction de la charge de phosphore dans les bassins versants est considérée comme l'option la plus viable dans la diminution de l'eutrophication. En observant une tendance avec des charges de sédiments dans un bassin versant, il a été conclu que les charges en phosphore sont liées aux modèles de perte de sol et, par conséquent, aux changements dans l'affectation des sols en amont. L'utilisation d'un modèle d'érosion approprié a permis de déterminer l'impact des changements dans le bassin versant sur les charges en sédiments et en phosphore dans un stockage urbain et d'étudier diverses pratiques de gestion.

ABSTRACT

The impact of soil loss from urban erosion processes is a major problem confronting decision makers on a national and local level. The purpose of the study was to quantify what impact soil erosion, as a result of changes in land-use, had on urban impoundments.

The management of sediment loads combined with reduced catchment phosphorus loading is viewed as the most viable option in eutrophication abatement. By observing a trend with sediment loadings in a catchment, it was concluded that the phosphorus loadings relate to the soil loss models and hence changes in the upstream land-use.

Using a suitable erosion model, the impact catchment changes have on the sediment and phosphorus loadings of an urban impoundment was determined and various management practices were investigated.

KEYWORDS

Land-use change, Soil Loss, Urban Impoundments

1 INTRODUCTION

Impoundments in urban areas of South Africa, either natural or artificial, are popular recreational attractions that add to the quality of life, increase property value and are increasingly built as focal points for commercial developments. More regularly such impoundments acts as receptacles for polluted runoff, resulting in water quality problems which ultimately reduce the aesthetic value and undermine their recreational value and function as originally envisaged (Freeman et al, 2000).

The impact of soil loss from erosion processes is a major problem confronting decision makers on a national and local level due to the impact on local resources (Le Roux et al, 2007). One such resource is the Boksburg Lake in the Eastern Service Delivery Region of the Ekurhuleni Metropolitan Municipality of the Gauteng Province, South Africa. The Problem is due, in part to the reluctance of municipal officials primarily involved with storm water infrastructure and catchment management to undertake seemingly non-technical issues such as dealing with causes of erosion in the urban environment and partly because it is viewed as a social behavior and environmental management problem rather than an engineering consideration (Armitage & Marais, 2003).

The purpose of the study is to quantify what impact soil erosion processes, as a result of changes in land-use, will have on urban impoundments, Boksburg Lake in this case study. The impact is assessed through the compilation of a computer based simulation model.

Boksburg Lake, located in Boksburg, a service delivery center of the Ekurhuleni Metropolitan Municipality within the Gauteng provinces is a shallow, urban hypertrophic dam as per OECD (Organization for Economic Cooperation and Development) classification (Annex 1, p 92) (Vollenweider & Kerekes, 1980). The dam has been in a polluted state for at least two decades with an increase in fish mortality rates (South Africa. Ndumo Group Projects, 2008). This is primarily because of the increased rate of pollution.

There is a close relationship between how land is managed and the impact erosion (and hence phosphorus) may have on in-stream health. Increased erosion as a result of catchment changes increases the possible loads of phosphorus introduced into streams (Croke, 2002) and subsequently increases the occurrence of eutrophication. Recent research has discovered that existing stores of sediment, resulting from previous erosion (mid–to-long term), are responsible for the delivery of additional phosphorus to waterways and reservoirs (Croke, 2002). The management of sediment levels combined with reduced catchment phosphorus load is viewed as the most viable option in eutrophication abatement. This is due to phosphorus release from low-oxygen sediments in riverbeds and reservoir sediment layers (Croke, 2002).

The aim of the study is to quantify the sources and mechanisms of urban erosion occurring in urban catchments. This will be achieved through the compilation of a soil loss model using a similar methodology proposed by Moojong et al (2008), applying a modified approach of a soil loss model (in Moojong's case, the Revised Universal Soil Loss Equation), suited for urban conditions. This approach will be adopted for South African rainfall and soil conditions. Considerations and recommendations for the reduction of the external nutrient loads (specifically phosphorus) will be presented.

2 STUDY SITE DESCRIPTION

Boksburg Lake is a shallow urban lake situated within the city center of Boksburg, falling within the Ekurhuleni Metropolitan Municipality (EMM) (Figure 1), Gauteng province of South Africa.

The lake catchment is 29.43 km^2 in size (was sub-divided in 529 catchments) with an average percentage imperviousness of 36% with a predominantly commercial and industrial land-use, some residential and open spaces but mainly in the upper reaches of the catchment. The southern and south eastern portions of the catchment are business districts and residential dwellings. A rapid rate of development was experienced in Boksburg over the last few decades (South Africa. Ekurhuleni Metropolitan Municipality, 2010). The rapid rate of development invariably puts pressure on the local environment.

The rate of urban development is illustrated in Figure 2, below. It is expected that the soil loss annual yield will follow a similar trend as the effect of development (urban sprawl) is much greater than the effect of rural use (Laker 2012). The above reflect an average annual development increase of 19.4%.The comparison and development graph is only based on visible developments that took place in this period and does not give a true representation of densification (determined using satellite imagery from 2000 and land use maps for the years 1995 to 2000). There is still a significant amount of vacant land open for development. This represents an opportunity for substantial urban infill and densification and hence put pressure on existing engineering and social infrastructure.

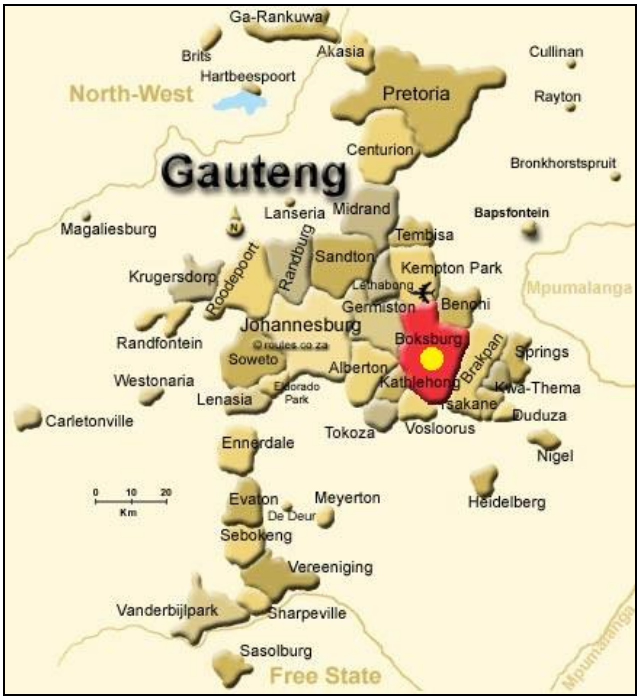

Figure 1. Locality Map of Boksburg Lake (from http://www.routes.co.za/gp/boksburg/)

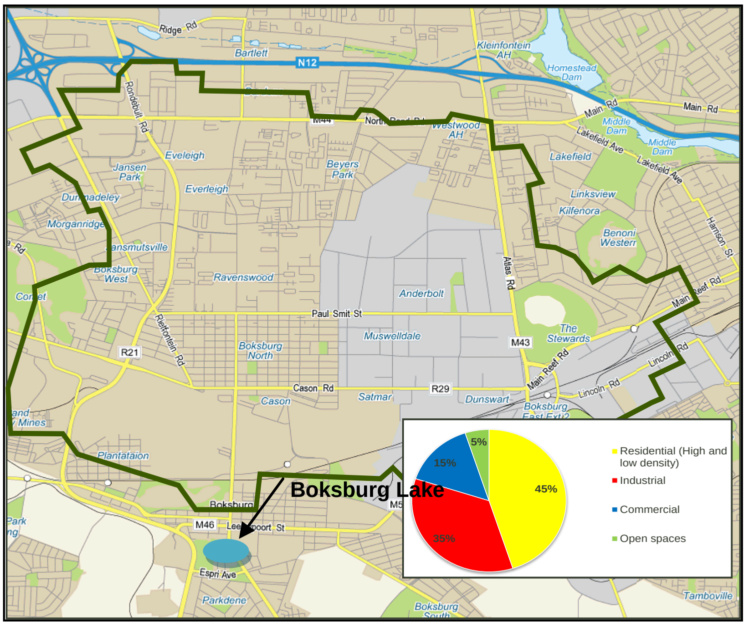

Figure 2. Catchment and Land-use distribution within the Boksburg lake catchment

The capacity of the lake and silt volumes was determined through bathymetry and sub-surface profiling. At the time of the survey in late 2010/ early 2011, the lake was 35% silted. This yields an average siltation rate of 10 042 m^3 (minimum of 9 718 m^3 and maximum of 10 366 m^3) or 19 375 tons annually considering a linear increase from 1996. For the simulations of soil loss yield, full years (January to December) were considered yielding a total of 170 731 m^3 from 1996 to 2011 (35% silt capacity). (refer to Figure 3, below)

Based on this linear trend, the lake has a remaining life expectance of another 26 years (2041). Sampling of the sediment material conducted by independent laboratories in 2011 indicated silt densities ranging between 1 898 and 2 116 kg/m^3. Using 2 000 kg/m^3, the estimated tonnage of silt material for the period amounts to 311 x 10^6 kg.

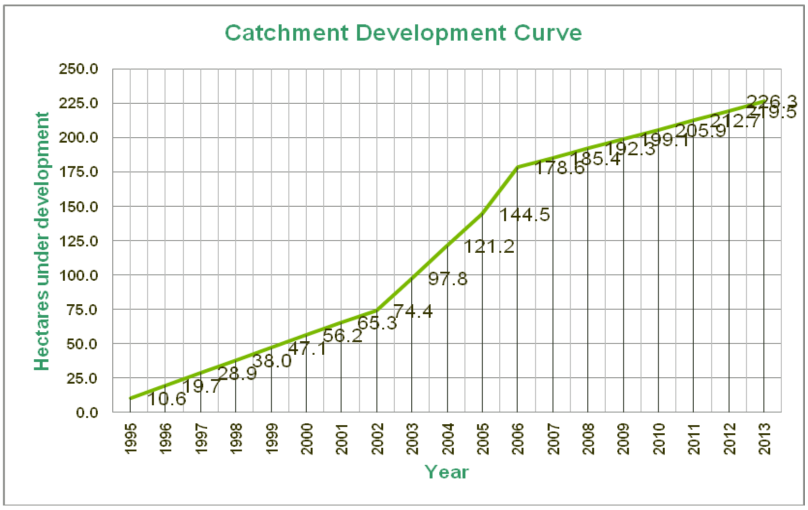

Figure 3. Rate of development from 1996 to 2013

3 MODEL SELECTION AND MODELING

Various erosion models exist and have been in use, but not all are suited to the application and intended purpose of this study. Two models were selected following a selection proces, they were a) Universal Soil Loss Equation (USLE) and b) Soil Loss Estimation model for South Africa (SLEMSA). Both were adobted for South African conditions. Sediment delivery ratios and effective contribution fractions were applied to the models to analyze the effect on the sediment yield.

Within catchments not all eroded material is transported to the outfall, as deposition and storage occurs along the slopes. To account for this reduction in yield, a proportion representing the amount of eroded soil reaching the outfall is used. It is known as the sediment delivery ratio (SDR) or index.

Delivery ratios try to account for catchment characteristics but there is no precise procedure to estimate the SDR (Kim, 2006). Three specific equations were applied namely; USDA SCS, Vanoni, and Boyce equations (drainage area approaches).

With the delineation of sub-catchments two distinct areas are identified, namely impervious and pervious areas. Impervious areas are considered as covered with an impermeable layer (e.g. concrete or asphalt) with no soil loss contribution. They must not be confused with bare soil areas where soil loss does occur although having lower infiltration rates (like construction plant laydown areas).

Within catchments not all eroded material is transported to the outfall, as deposition and storage occurs along the slopes, behind buildings and other obstructions. This is the basic principle behind sediment deliver ratios. Within urban catchments, artificial barriers are also encountered in the form of fences and gardens where deposition occurs due to ponding and low flow velocities. These areas are can be considered as being cut off from the soil loss contributing catchment.

Actual contributing catchment percentages were calculated based on aerial photography and on-site inspections and related to the land-usage for ease in the model. Land-usage was related to imperviousness as part of the hydrological model. The results are presented in Table 2.

Table 2 Effective Catchment Contribution (ECC) factor related to imperviousness

Imperviousness (%)	ECC* (fraction)
60	0.1
50	0.2
45	0.3
40	0.4
35	0.7
30	0.8
25	0.85
5	0.95

4 MODEL RESULTS

Various scenarios were modelled using the two methods selected. Baseline models were calibrated using the 2010/2011 land-use and cover information. The years 2010/2011 was selected because it coincided with the year the sub-surface survey was done to determine the silt volumes in the lake. Four model scenarios were compared using the parameters and factors discussed. The scenarios were applied using both SLEMSA and USLE. The scenarios are:

- Basic model: only applying the factors required for the model construction. No delivery ratios or adjustment factors have been applied.
- Sediment Delivery Ratio: Applying Sediment delivery ratios to the basic model. Three ratios were compared
- Effective Contribution Catchment: applying the effective contributing ratio of catchment
- 50% Delivery ratio: Constant factor of 0.5 applied to all catchments

The volume of soil lost for the year 2010/2011 was calculated. The obtained volume was cumulatively added from the simulation start of 1995/1996 assuming a linear increase until the end of 2011. The total volumes were compared to that of the sub-surface survey. The above was done to obtain an indication as to which model methodology will compare the best. The results of the simulations are presented in the following table.

Table 3 Model comparison

Model	Volume Calculation (m^3)	Over or under estimate	Annual estimate (m^3)
Measured volume	155,485	0%	10,366
USLE (BASIC)	266,835	71.61%	17,789
USLE (SDR USDA)	201,765	29.76%	13,451
USLE (ECC)	133,065	-14.42%	8,871
SLEMSA (BASIC)	310,350	99.60%	20,690
SLEMSA (SDR USDA)	233,955	50.46%	15,597
SLEMSA (ECC)	160,875	3.46%	10,725
USLE (50%SDR)	133,425	-14.19%	8,895
SLEMSA (50%SDR)	155,175	-0.20%	10,345
USLE (SDR Vanoni)	175,410	12.81%	11,694
SLEMSA (SDR Vanoni)	203,310	30.75%	13,554
USLE (SDR Boyce)	245,565	57.93%	16,371
SLEMSA (SDR Boyce)	283,560	82.37%	18,904

Both basic models yielded soil loss estimates higher than the sediment volume of 155 485 m3.The USLE estimate is 71.6% higher and SLEMSA 99,6%. Three sediment delivery ratios were applied namely the USDA SCS, Vanoni equation, and Boyce equation. The USDA SCS method decreased the basic USLE and SLEMSA models within 29.76% and 50.46%, respectively. The results from the Vanoni equation decreased the model yields to within 12.81% and 30.75%, respectively. Compared to the USDA SCS and Vanoni equations the Boyce equation only managed to decrease the yield to within 57.93% and 82.37% within the measured results for the USLE and SLEMSA models respectively. The Vanoni equation provides the best results.

Additional to the application of the sediment delivery ratios, the Effective Contributing Catchment (ECC) was also applied and yielded results -14.42% and 3.46% within the measured results, USLE and SLEMSA respectively. This is also within acceptable limits. As a last measurement an average sediment delivery ratio of 50% was applied. These yielded results within -14.19% and -0.2% for the USLE and SLEMSA models respectively. The application of a 50% ratio is an unverified method and can only be used as a quick measure.

Results from five of the models yielded results within 15%, or 85% confidence, of the measured results. Four of these models are however not generally accepted methods and can only be used as indication. The USLE method utilizing the Vanoni SDR equation is the preferred method and will be applied in subsequent modelling with the USLE ECC for comparison only. The results of the model comparison are further illustrated in the graph below (Eighty five percentile line indicated in grey).

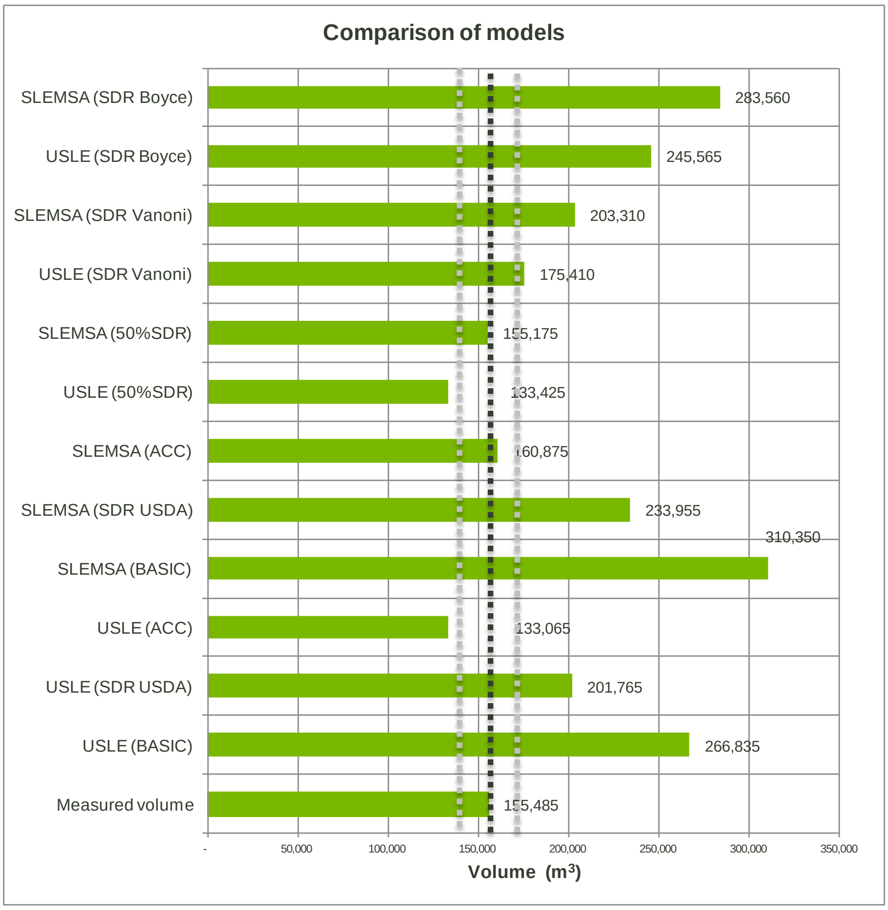

Figure 4. Comparison of models graph

To verify if the annual soil loss yield correspond to the development trend represented in Figure 3 erosion models were compiled for the years 1995, 2002, 2005, 2006, 2010, and 2011, each considering land use changes within each timeframe. The results of the simulations are summarized in Table 4 and Figure 5. Also indicated in Figure 5 is an upper and lower confidence level within 10% of the measured results. Without development 154 309 m^3 soil would have entered the lake over the simulation period. With an annual increase in development of 19.4% a total of 176 222 m^3 is expected.

Table 4 Model comparison

Model	USLE 1995	2002	2006	2011	Average volume	Volume 1995 to 2011
BASIC	**10366**	**10366**	**10366**	**10366**	**10,366**	**176,222**
Basic USLE	13714	14596	16193	17,789	15,375	261,367
ECC USLE	7158	7165	8337	8,871	7,775	132,169
SDR USDA USLE	10432	11075	12263	13,451	11,657	198,177
Vanoni USLE	**9077**	**9633**	**10664**	**11,694**	**10,139**	**172,357**
Boyce USLE	12828	13563	14967	16,371	14,257	242,373
50% SDR USLE	6857	7298	8097	8,895	7,687	130,686
Basic SLEMSA	14995	15095	17892.5	20,690	16,799	285,589
ECC SLEMSA	**9443**	**9450**	**10296**	**10,725**	**9,897**	**168,254**
SDR USDA SLEMSA	11484	11543	13570	15,597	12,781	217,279
Vanoni SLEMSA	**10001**	**10050**	**11802**	**13,554**	**11,121**	**189,050**
Boyce SLEMSA	14270	14313	16608.5	18,904	15,721	267,252
50% SDR SLEMSA	7497	7548	8946.5	10,345	8,400	142,796

Three models compared favorable. The USLE model applying the Vanoni equation is within 2.19% with 172 357 m^3. The SLEMSA Vanoni model yielded results within 7.28% with 189 050 m^3 whilst the SLEMSA ECC came within 4.52% with 168 254 m^3.

The USLE Vanoni model again yielded the best results when compared to the indicative model. Contrary to the previous single model approach, the SLEMSA Vanoni model also yielded comparable results. From this can be concluded that the use of the Vanoni equation can be used with both SLEMSA and USLE when applied to urban areas. Also clear is that the same trend is followed as the development curve in Figure 3.

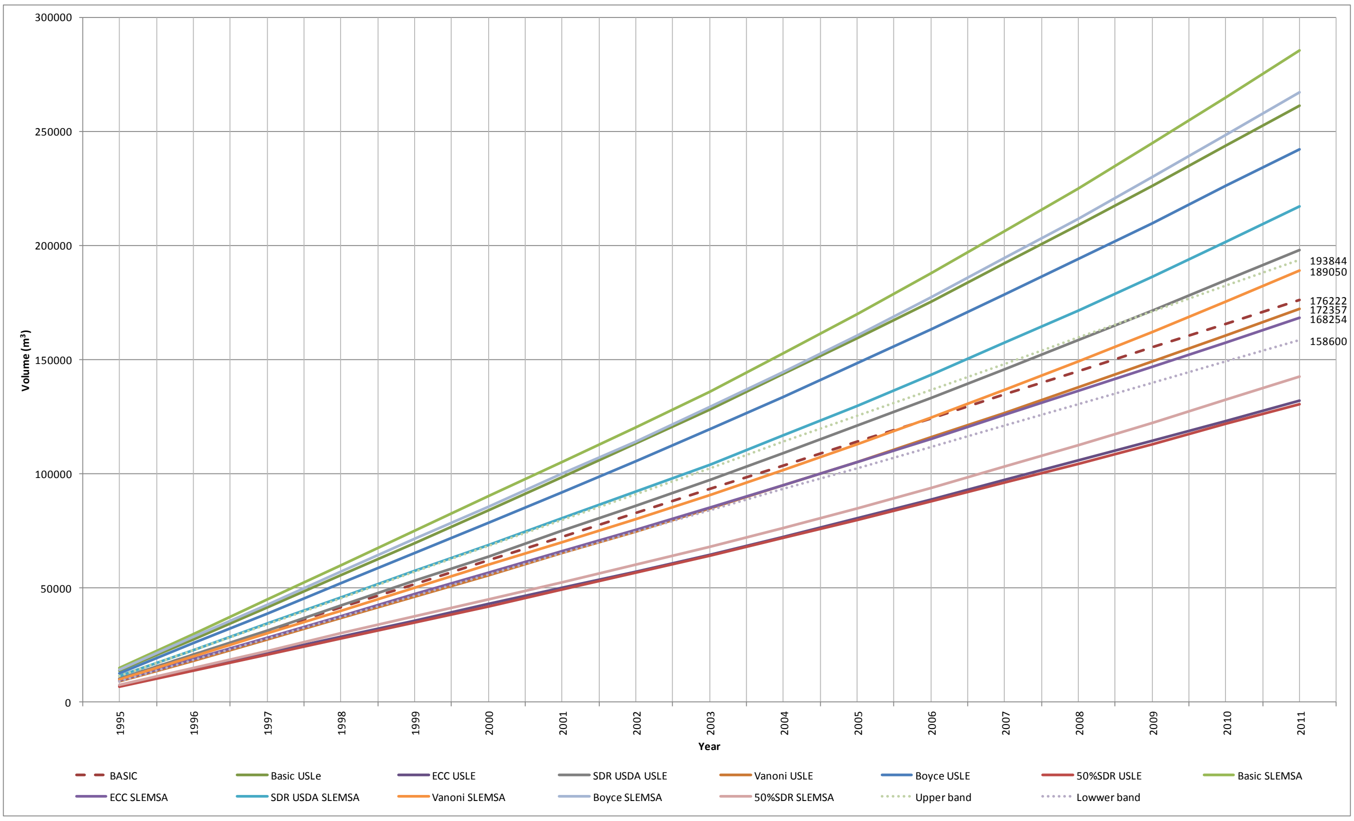

Figure 5. Comparison of models

4.1 Comparison of results between SLEMSA and USLE

The difference between the estimated losses using the two methods is large for most catchments although still comparable and highly correlated. It can be concluded that depending on the ease of determining the input variables and the level of accuracy required either of the two methods, and utilizing the Vanoni SDR equation, can be used to assess the level of soil erosion within urban environments. Also evident from the investigation was that further investigation and refinement of the ECC factors can yield highly comparable results. The models do give a clear indication that differences in soil loss volumes are experienced as a result of changing catchment conditions.

5 CONCLUSIONS

Two models, the Universal Soil Loss Equation (USLE) and the Soil Loss Estimator of Southern Africa (SLEMSA) were used to simulate soil loss for the Boksburg Lake catchment. The simulations were aimed at investigating if current available models can be utilized to investigate the impact land-use changes (i.e. changes in imperviousness due to development within the catchment) will have on soil loss concentrations to the Boksburg Lake.

The following conclusions can be drawn from the study:

- Many soil loss models are currently in use throughout the world. Not all are suitable for urban conditions and are primarily utilised for agricultural studies. Many of these models are empirically based with little spatial distribution and used for long term estimation. Few physically based models are in use with regards to urban modelling and even less can be generalised to other regions of the world other than the study area.
- Models, aimed at estimating phosphorus concentrations, are few in use. Most are aimed at eutrophication mass balancing for large reservoirs and do not consider localised urban lakes. Even less of these models can be generalised to a wider project area.
- The use of soil loss models is dependent on good and available datasets. This includes

information on the rainfall, topography, cover management practices and the soil characteristics. This proved to be a limiting factor in the selection of the models. A model utilizing daily rainfall data, although very favourable from an academic perspective, would have little interest to municipal managers having to deal with limited funding, personnel and resources as the level of complexity is considered too high for the level answer. SLEMSA and USLE were selected as they are easy to understand and apply, have simple parameters and have been used throughout Africa and Southern Africa.

- Direct application of the models (baseline) yielded losses 71.6% and 99.6% higher than the measured sediment volume of 155 485 m^3 which accumulated over the period from 1995/96 to 2011. Sediment Delivery Rations using drainage area approaches were applied to the baseline and multi-year models. Application of the Vanoni SDR equation yielded results within 12.8% and 30.8% for USLE and SLEMSA, respectively. These were not considered to be accurate enough as values fell outside the 15% confidence level.
- Application of Effective contribution and 50% SDR factors yielded results within 3.46% and -0.2% for SLEMSA and results within -14.42% and -14.19% for USLE when applied to the baseline models. Although the SLEMSA results are found to be within the confidence level, both factors are not generally accepted approaches to SDR calculations.
- The comparison of results between the two models (baseline and multi-year) indicates that differences in concentrations are high although a correlation can be drawn between the models. SLEMSA results were on average higher than USLE.
- Multiple scenarios were run applying different Sediment Delivery Ratios for both a base model and annual models. The baseline models, using a linear decrease from 2011 to 1995/6, yielded comparable results to the multi-year model.
- SLEMSA and USLE showed different degrees of sensitivity to their input variables. Both methods are sensitive to crop/cover management practices (SI values of 1.4 and 0.88, respectively), soil erodibility, and topographical changes (SI values of 1.32 and 0.89, respectively). USLE is less sensitive to erosivity. Of the above, changes in erodibility had the biggest influence. In an instance a 20% increase resulted in a 25% decrease.
- The study area, 29.43 km^2 in size, yielded a total runoff volume of 8.23 Mm^3. On average the dam would be filled 21 times per annum or every 17 days. Applying an observed total phosphorus concentration of 0.864 mg/l to each catchment's runoff, a total load of 8 187 kg should be expected.
- It is however not clear from the phosphorus analysis, due to the lack of available information, what the division is between ortho-and adsorbed phosphates. This can only be verified through further monitoring and sampling.
- It was observed that a correlation exist between changes in land-use, soil loss and total phosphorus loading.
- Two reduction measures were investigated and included in the management tool. With a street sweeping efficiency of 47%, the totals soil loss can be reduced from 11 121 m3 to 5 894 m^3 and the total phosphorus concentration from 8 187 kg to 4 339 kg per annum. Six sites have been identified for sedimentation retention basins. The combined efficiencies of the basins result in an estimated reduction of 86% of the annual losses.
- It can be concluded that both SLEMSA and USLE, applying the Vanoni SDR equation, can be applied to urban catchments with high levels of accuracy.

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